

The Force on the Cathode of a Copper Arc

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(Received February 7, 1938)

The force on the cathode in the electric arc, previously examined either in air at atmospheric pressure or in vacuum, is studied as a function of pressure. For the copper arc in nitrogen the force is found to remain of the order of magnitude of the values observed in air down to a pressure of about 5 mm, and then to increase sharply but smoothly to the much larger forces observed in vacuum. Various aspects of the arc are examined in this transition region. Curves showing force as a function of current at various pressures of hydrogen and nitrogen are given. A brief study of the stability of the vacuum arc is included, as well as a summary of the various theories put forward to explain the phenomenon.

INTRODUCTION

THE mechanical force exerted on the electrodes in the electric arc has been studied under two distinct sets of experimental conditions. On the one hand, various observers,¹⁻³ chiefly Duffield, Burnham, and Davis,^{1, 2} have measured the force on both cathode and anode in arcs of different electrode materials running in air at atmospheric pressure. The forces found in these measurements, in which currents up to 10 amperes were used, are of the order of a dyne per ampere. Studies have also been made,^{4, 5} in which hollow carbon electrodes and delicate manometers were used to determine the actual gas pressure at the electrodes. On the other hand, Tanberg⁶ has measured the force on the cathode of the copper arc in vacuum, finding the force to be about 17 dynes per ampere in the range 10-30 amperes. Creedy, Lucas and Easton,⁷ using currents as high as 150 amperes, found correspondingly high values for the force in the vacuum arc with several electrode materials. The force on the cathode in the mercury arc has also been the object of study.⁸⁻¹⁰

The lack of adequate experimental data has made the interpretation of these results very difficult. In particular, no studies have been made of the region intermediate between the two cases. It was therefore decided to study the force on the cathode of the copper arc at different pressures. Nitrogen was used instead of air in order to effect some simplification of the already complicated experimental conditions. The present paper is an attempt to summarize the results obtained in such a form as to be of most use to those desiring to pursue the subject further. No final conclusions can be drawn as to the nature of the force, but it is shown that there is a continuous transition, occurring in the region below 5 mm, from the small forces found at higher pressures to the large forces found at lower. Curves are shown for force as a function of current for pressures up to 500 mm, but it is the writer's opinion that measurements at the higher pressures, while qualitatively instructive, are of little value from the quantitative point of view because of disturbing effects notably convection and chemical action.

The statement has been made⁶ that "an electric arc can be drawn even in very high vacuum by separating two metal contacts carrying current of the order of a few amperes." Some tests were carried out under reasonably clean surface

TABLE I. *Conditions under which a copper arc would not operate.*

p (MM)	V_0 (VOLTS)	i_s (AMP)
10 ⁻³ - 10 ⁻⁵	115	0 - 30
	230	0 - 30
	600	0 - 10

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¹ Duffield, Burnham and Davis, *Phil. Trans. Roy. Soc. A220*, 109 (1920).

² Duffield, Burnham and Davis, *Proc. Roy. Soc. A97*, 326 (1920).

³ Sellerio, *Phil. Mag.* **44**, 765 (1922).

⁴ Dewar, *Proc. Roy. Soc.* **33**, 262 (1882).

⁵ Beer and Tyndall, *Phil. Mag.* **42**, 956 (1921).

⁶ Tanberg, *Phys. Rev.* **35**, 1080 (1930).

⁷ Creedy, Lucas and Easton, *Trans. A.I.E.E.* **53**, 1454 (1934).

⁸ Stark and Reich, *Physik. Zeits.* **4**, 323 (1902).

⁹ Stark and Cassuto, *Physik. Zeits.* **5**, 269 (1904).

¹⁰ Kobel, *Phys. Rev.* **36**, 1636 (1930).

and vacuum conditions to define the region of stable arcing. The arc was considered stable if on separating the electrodes a discharge persisted for as long as 15 seconds. In the first place it was established that no copper arc would run in the residual gases of the system under the conditions given in Table I. p is the pressure in mm as read on the McLeod gauge, V_0 the open circuit voltage and i_s the short circuit current. The ranges given indicate the range tried and do not necessarily mean that the arc is stable for points outside. In the second place, tests were carried out for the copper arc in nitrogen at $i_s = 20$ amperes and $V_0 = 230$ volts. The region of stable arcing was found to extend down to about 0.1 mm, below which pressure no arc of any length whatsoever could be maintained. No appreciable increase in range of stability was effected by the introduction of inductances of various sizes into the circuit. It would appear that further study of the stability of the so-called vacuum arc is desirable.

A pendulum deflection method of measuring the force was decided upon as being easiest to manipulate in a closed chamber. In such an experiment the measured total force is made up of a number of components. Most of the forces encountered tend to increase the arc length and such forces will be referred to as "positive." Those such as convection tending to decrease the arc length are called "negative." There are electromagnetic forces caused by interaction of the current, I , in the pendulum with both the earth's field and the field due to the rest of the circuit. These are proportional to I and I^2 , respectively. Electrostatic forces, depending on the potential distribution between the electrodes are negligibly small. A disturbing factor, which cannot readily be evaluated is convection, which we will take to include all effects due to large scale movements of the surrounding gas. Radiometer forces are small but must be considered in a full account. Evolution of occluded gases, suggested as a possible cause of the high vacuum forces,¹¹ would produce a transient effect.

Any forces measured which cannot be attributed to a combination of the above forces must be explained by effects intimately connected with the arc mechanism. To account for the

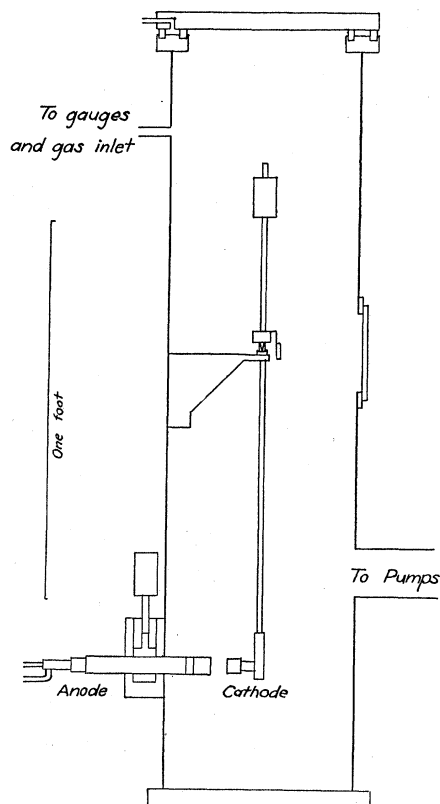


FIG. 1. Schematic diagram of the apparatus used in this work.

observed facts several theories have been put forward. Electrons emitted from the cathode spot will produce a reaction force of the right order of magnitude to explain that observed at the higher pressures. This was suggested by Duffield.^{1, 2} A vapor stream emerging from a high temperature region at the cathode would give such a force. Tanberg and his co-workers^{6, 12-14} put forward this theory to explain the force in the vacuum arc. The hypothesis was supported by the fact that a force was observed on a vane suspended in front of the cathode. Ions falling through the cathode fall of the arc and remaining on the electrode after neutralization produce no net force. However if the atoms come off after neutralization with a fraction $(1-\alpha)$ of their incident kinetic energy, where α is the accommodation coefficient for ions, a reaction force is pro-

¹² Berkey and Tanberg, Phys. Rev. **38**, 296 (1931).

¹³ Berkey and Mason, Phys. Rev. **38**, 943 (1931).

¹⁴ Mason, Elec. Eng. **52**, 702 (1933).

¹¹ Wellman, Phys. Rev. **38**, 1077 (1931).

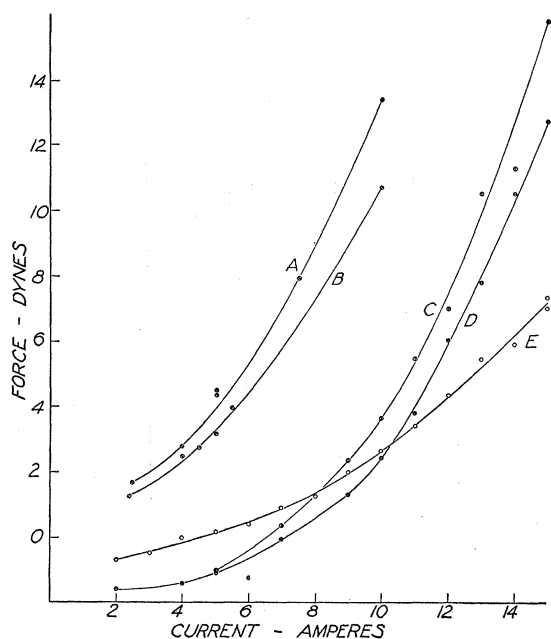


FIG. 2. Force on the cathode of a copper arc, arc length 5 mm, running in *A*, hydrogen at 50 mm pressure; *B*, hydrogen at 100 mm pressure; *C*, nitrogen at 20 mm pressure; *D*, nitrogen at 100 mm pressure; *E*, nitrogen at 500 mm pressure.

duced. Compton^{15, 16} has shown that for reasonable assumed values of α this force is of the right order of magnitude to explain the force in vacuum. Tonks¹⁷ calculated the force due to plasma electrons which were reflected from the cathode sheath and found that large forces could thus be accounted for. Risch and Ludi^{18, 19} have suggested that there may be a large number of atoms near the cathode ionized as many as five or six times. If there is a sort of accommodation coefficient whereby some of the energy of ionization is turned into kinetic energy of rebound when the ion strikes the cathode, a large force could be accounted for. It should be noted that none of these theories points to a satisfactory explanation of the observed variation of force with pressure.

EXPERIMENTAL METHOD

In Fig. 1 are shown the main features of the experimental setup. The pendulum was mounted

¹⁵ K. T. Compton, Phys. Rev. **36**, 706 (1930).

¹⁶ K. T. Compton, Proc. Nat. Acad. Sci. **18**, 705 (1932).

¹⁷ Tonks, Phys. Rev. **46**, 278 (1934).

¹⁸ Risch, Helv. Phys. Acta, **4**, 122 (1931).

¹⁹ Ludi and Risch, Zeits. f. Physik. **75**, 813 (1932).

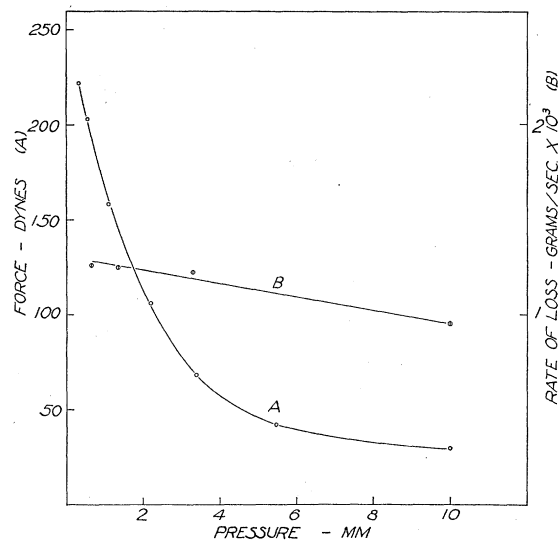


FIG. 3. *A*. Force on the cathode of a copper arc, current 15 amperes, arc length 1 cm, in nitrogen. *B*. Rate of loss of material from the cathode of a copper arc under the above conditions.

in a brass tank with removable top, which could be evacuated by means of a large Apiezon oil pump, the resulting pressure being measured on a McLeod gauge. Liquid air was used to keep mercury vapor from the gauge and oil vapor from the pumps out of the system. The best vacuum obtainable was about 10^{-6} mm. Gases were introduced into the system through purifying devices to remove water and oxygen, pressures above 10 mm being measured on a closed end manometer.

The pendulum consisted of a Duralumin rod supported on steel points resting in steel cups. The copper cathode rod was mounted in an aluminum block at the lower end of the pendulum. At the top was an adjustable counterweight which controlled the sensitivity. It was necessary to surround the cathode with a quartz sleeve to keep the cathode spot from wandering. The copper was turned down a little near the end to leave a small gap between it and the quartz. The current was brought into the pendulum by means of fine wires led down from a bar above to side arms at the axis of the pendulum. About one or two number 40 copper wires per ampere were sufficient. The effect of these wires on the sensitivity was tested and found to be negligible.

The external circuit was arranged to reduce electromagnetic effects to a minimum, but it was

necessary to mount the pendulum with its axis of rotation in a north and south direction, so that a "negative" force is present owing to interaction of the current in the pendulum with the earth's field. The current travels vertically in the pendulum for 25.4 cm below the axis and horizontally in the cathode rod for 2.5 cm. The anode rod, which was fixed and parallel to the cathode, was 22.9 cm in length.

The arc was started by contact between the cathode and the water cooled copper anode, which could be moved backward and forward through an Apiezon grease and graphite packed joint. Since the damping in the pendulum was very small, the anode and cathode had to be separated with great care to prevent violent oscillation being set up. With high currents and large forces the pendulum was often kicked away violently when the arc struck. Therefore a device was introduced consisting of an arm controlled through a packed joint which held the cathode steady while contact was being made. The arc length was measured by means of an enlarged image of the arc thrown on a screen.

The pendulum deflection was measured with a mirror mounted at the axis of the pendulum and a scale 2.2 meters away. The sensitivities used varied from 0.3 dynes per mm to 10 dynes per mm. Readings were taken in the following manner. The arc having been started and the current adjusted, the pendulum was in general in motion with small amplitude. For long periods, a cross hair was focused on the vertical scale and readings were taken of successive maxima and minima with the arc running and then with the arc extinguished. The difference between the mean positions was calculated and by the use of the previously determined sensitivity the force was found. For short periods, when readings could not be taken directly, a photographic method was used. The image of a horizontal line filament was focused on a strip of bromide paper. With the arc running the light source was turned on and the image allowed to move up and down a few times. The source was then put out and the arc extinguished. The paper was then displaced slightly and the light turned on to record the zero. It is not necessary to move the paper continuously since the successive maxima are marked by quite sharp lines on the developed paper.

EXPERIMENTAL RESULTS

In Fig. 2 is shown the result of measurements made of force as a function of current for different pressures of nitrogen and hydrogen down to 10 mm. The points plotted are actual experimental points to which no corrections have been applied. No quantitative correction being possible for some extraneous effects, convection in particular, it was considered useless to apply any others. In general, points were taken both ascending and descending the curves to check the reproducibility of the effect. In this experiment the diameter of the cathode was $\frac{1}{4}$ inch and the arc length 0.5 cm. The forces found are of the same order of magnitude as those observed by Duffield, Burnham, and Davis. At low current the force is negative for nitrogen. In hydrogen the force is greater than in nitrogen and there is no tendency to negative forces. In both cases the force increases slowly with decreasing pressure. These facts may be explained in terms of convection effects which would be smaller for hydrogen and for lower pressures of either gas. The difference in shape between the curve for nitrogen at 500 mm and the other two nitrogen curves was

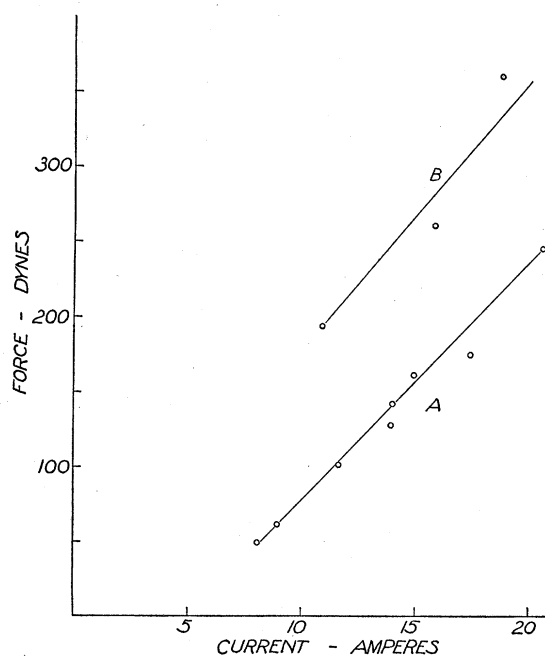


FIG. 4. A. Force on the cathode of a copper arc, arc length 1 cm, in nitrogen at 1 mm pressure. B. Force observed by Tanberg in the vacuum arc.

accompanied by a change in the form of the arc from type II (Hagenbach's notation²⁰) where the red anode end of the arc is concentrated at a point to type I where the anode end is a diffuse red glow.

Thus for pressures as low as 10 mm there is no sign of the large forces observed by Tanberg in the vacuum arc. Fig. 3, however, shows the result of a series of measurements of force as a function of pressure for the 15 ampere copper arc in nitrogen. The cathode diameter was 0.3 inches and the arc length 1 cm. The force is seen to rise from a value at 10 mm comparable to that observed by Duffield, Burnham, and Davis to a force at 0.3 mm of the order of magnitude of that found by Tanberg in the vacuum arc. In this transition region several aspects of the arc were examined for possible correlation:

(1) Appearance. There was no marked change in the appearance of the arc apart from a gradual broadening with decreasing pressure.

(2) Voltage. The arc voltage remained constant at about 20 volts throughout the range.

(3) Material lost by the cathode. Some measurements were taken of the loss of material per second as a function

²⁰ Hagenbach and Veillon, *Physik Zeits.* **11**, 833 (1910).

of pressure. The cathode rod was weighed before and after a 30 second period of arcing at 15 amperes. The result is shown in Fig. 3, curve *B*. There is no apparent correlation. The values found are much larger than those observed by Tanberg who observed a rate of loss at 15 amperes of about 0.23 milligrams per second.

It is clear from these results that the transition to the high forces is gradual, and that the high force is not characteristic of a special type of discharge setting in discontinuously at low pressures.

In Fig. 4 are given results of measurements taken in nitrogen at 1 mm pressure of force as a function of current. Some of Tanberg's vacuum arc figures are given for comparison. The chief difficulty in these measurements is the tendency of the arc to strike in the crack between quartz and copper. The force is then greatly reduced. This might lead to the supposition of two types of vacuum arc if the arc were not visible to the observer.

In conclusion I should like to thank those who have cooperated with me in this research, particularly Professor E. S. Lamar whose constant contact with the work has been a source of inspiration and genuine assistance and Dr. K. T. Compton who has offered much helpful advice.

Internal Friction in Solids

IV. Relation Between Cold Work and Internal Friction

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(Received February 7, 1938)

Previous investigators have found that cold working of metals has a marked effect upon internal friction, increasing it, in certain cases, by a factor of more than ten. In the present paper it is assumed that the effect of cold work upon internal friction is due to the residual internal stresses which it produces. During vibration these residual stresses give rise to fluctuations in temperature, and thus to local heat currents, which are inevitably associated with a rise in entropy, i.e., with internal friction. A formula is obtained

for this internal friction in terms of the energy associated with the residual stresses, and the temperature variation of the modulus of rigidity. It gives the observed order of magnitude. According to the theory developed in this paper, the measurement of the internal friction of a cold worked specimen over a wide frequency range and for various types of vibration will give not only the mean square of the residual stresses, but also their preferred axes, if any, and the mean linear dimensions of their inhomogeneities.

§1. INTRODUCTION

THE writer has recently investigated, both theoretically and experimentally, that part of the internal friction of solids which is associ-

ated with stress inhomogeneities.¹⁻⁴ These stress

¹ C. Zener, *Phys. Rev.* **52**, 230 (1937).

² C. Zener, *Nature* **140**, 895 (1937).

³ C. Zener, *Phys. Rev.* **53**, 90 (1938).

⁴ C. Zener, W. Otis, R. Nuckolls, *Phys. Rev.* **53**, 100 (1938).